

BRACHINITE HIGHLY SIDEROPHILE ELEMENT SYSTEMATICS INDICATE RETENTION OF A Pt-RICH PHASE DURING CHONDRITE MELTING. R. W. Nicklas¹, J. M. D. Day¹, Z. Vaci², M. Ren³ ¹Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA. Email: rwnicklas@ucsd.edu, ²Earth and Planetary Science Department, Washington University in St. Louis, St. Louis, MO 63130, USA, ³Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV 89154, USA

Introduction: Brachinites are primitive olivine-rich achondrites formed as residues of chondritic partial melting^{1,2}. The brachinite parent body (BPB) never completely melted, offering an important “snapshot” of planetesimal differentiation processes. The BPB experienced partial metal segregation as well as silicate melt removal from its mantle, as evidenced by the depletion in siderophile and incompatible lithophile elements in bulk brachinites^{2,3}.

Typical brachinites have olivine forsterite numbers (Fo) ranging from 60 to 70; lower than other primitive achondrites such as winonaites, acapulcoites and ureilites¹. The high quantity of Fe incorporated in silicates in brachinites has been attributed to relatively high oxygen fugacity (f_{O_2}) during their formation, ranging from iron-wustite (IW) -2 to -1⁴. In addition to brachinites, mineralogically similar olivine-rich meteorites have been recovered with Fo > 70 and similar oxygen isotope systematics². These meteorites, which also contain orthopyroxene that is absent in brachinites, have been termed “brachinite-like achondrites” (BLA)². Brachinites and BLA likely form a continuum of partial melt residue compositions on a single parent body^{2,4}.

Highly siderophile elements (HSE: Re, Os, Ir, Ru, Pt, and Pd) strongly partition into metal over silicate with $D^{\text{metal/silicate}} > 10^4$. The HSE are excellent tracers of metal-silicate partitioning and have been used to show that brachinites and BLA are melt residues and not olivine cumulates^{2,4,5}. This study reports new whole-rock and *in situ* HSE abundance systematics in a suite of four brachinites and BLA and descriptions of two previously unanalyzed meteorites: Northwest Africa (NWA) 6874 and NWA 7499. These data, when combined with previous HSE data for olivine-rich achondrites, show that Pt-rich alloys are retained during chondritic melting.

Methods: Aliquots of the brachinites and BLA NWA 6874, NWA 7499, Reid 013 and Miller Range (MIL) 090805 were obtained from the *Meteorite Working Group* and the *Institute of Meteoritics (IOM)* at the *University of New Mexico*. Bulk rock major and trace elements were performed by ICP-MS for NWA 7499, NWA 6874 and Reid 013 at UCSD using previously established techniques³. Bulk rock HSE abundances of all samples were determined by Carius tube digestion isotope dilution TIMS and ICP-MS at UCSD³. Polished thin sections were prepared for *in situ*

major and trace element analyses. Major element analyses of major phases were performed by electron microprobe at UNLV for NWA 7499 and NWA 6874 for which mineral data were unavailable. Olivine, metal and oxide phases were analyzed for their HSE contents by LA-ICP-MS in all samples using HSE-rich metal and sulfide LA standards at UCSD⁵.

Results: Based on average olivine compositions, Reid 013 (Fo₆₆) is classified as a brachinite, while NWA 7499 (Fo₇₀), NWA 6874 (Fo₇₁) and MIL 090805 (Fo₇₄) are BLA. Whole-rock REE abundance patterns of brachinites and BLA show broad scatter likely reflecting both terrestrial weathering (especially in Reid 013) and REE being hosted in minor phases (i.e. clinopyroxene) (**Figure 1**).

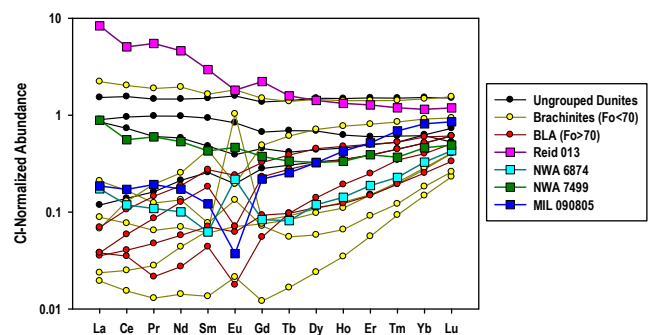


Figure 1: Bulk rock CI-chondrite normalized [6] REE in the samples and other brachinites, BLA and ungrouped dunitic achondrites [2-4]. Depleted patterns are consistent with a residual origin.

The HSE patterns show higher concentrations and positive Pt anomalies in BLA relative to brachinites (**Figure 2**). MIL 090805 shows the highest total HSE concentrations (57 ppm) of any known olivine-rich achondrite with an especially strong enrichment in Pt (11 ppm). Bulk rock Pt enrichment shows correlation with average olivine Fo (**Figure 3**). Platinum is more incompatible than Os, Ir, and Ru during terrestrial mantle melting, making the high $(\text{Pt}/\text{Ir})_N$ observed in the high-Fo BLA notable. Additionally, Pt and Pd behave similarly in terrestrial rocks, but are decoupled in brachinites and BLA (**Figure 2**). Olivine and oxide phases show negligible (below detection limits) HSE abundances, while metal phases have very high HSE concentrations up to 879 ppm (in NWA 6874) (**Figure**

4). Palladium is depleted in the metal phases, like the bulk rocks, but Pt/Ir ratios do not reach values shown in the bulk rocks.

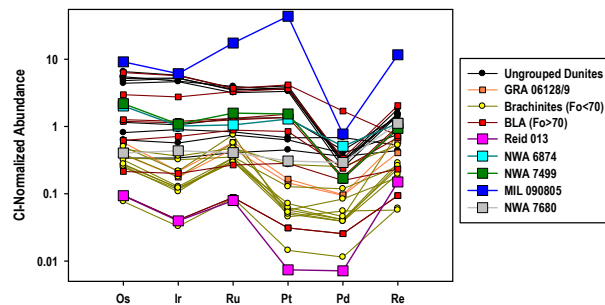


Figure 2: Bulk rock CI-chondrite normalized HSE patterns for olivine-rich achondrites^{2,3,4}. Note the superchondritic concentrations and positive Pt anomalies for BLA. Normalization from [7].

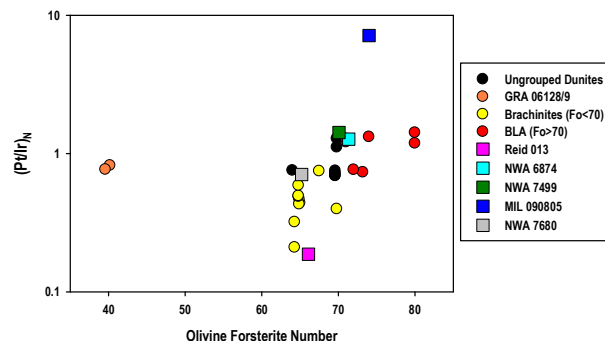


Figure 3: Bulk rock CI-chondrite normalized Pt/Ir ratios compared with average olivine Fo in olivine-rich achondrites and the brachinite-related felsic achondrites GRA 06128 and GRA 06129^{2,3,4}.

Discussion: Although brachinites are in some ways analogous to terrestrial depleted peridotites, they have only experienced incomplete core formation, leaving them with both a trace Fe-metal phase and high HSE abundances. Although REE patterns can be used to constrain the extent of melt removal in residual peridotites, they are subject to resetting by metasomatism and terrestrial weathering. The ease of this resetting is partially due to the REE budget in olivine-rich achondrites being dominated by modally minor clinopyroxene.

Olivine Fo contents also increase as more melt is extracted due to the incompatibility of Mg relative to Fe. As olivine is the dominant mineral in olivine-rich achondrites, its composition is difficult to reset. However, olivine Fo in meteorites also reflects the oxygen fugacity of core formation. Higher fO_2 leads to more Fe being hosted in silicates and lower Fo. Given

the oxygen isotope systematics of brachinites and BLA^{2,3}, they likely formed on a single parent body and their continuum of olivine Fo reflects increasing degrees of partial melting and potentially varying fO_2 ³. Using data for H ordinary chondrite melting at brachinite-relevant conditions, the range of Fo in brachinites and BLA is produced by 9.2-17.8% silicate melt removal⁷.

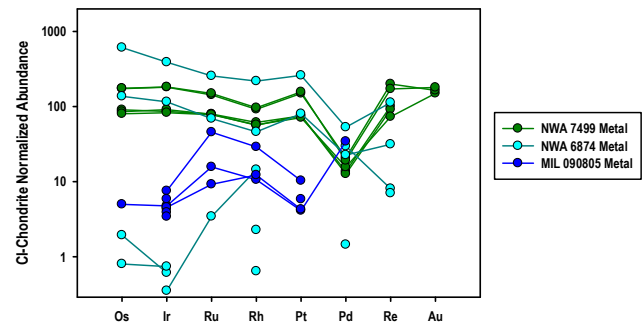


Figure 4: CI-chondrite normalized HSE abundances for Fe-metal and altered Fe-metal phases.

As the analyzed Fe-metal phases do not show the high Pt/Ir and positive Pt anomalies of the bulk rocks (**Figure 4**), variable Fe-metal enrichment is unable to explain the correlation shown in **Figure 3**. Therefore, a refractory Pt-rich phase is likely to be retained during high-degree (up to 18%) silicate melting. Although previous studies³ have invoked the presence of a Pt-rich sulfide phase (pentlandite) in brachinites, pentlandite has a relatively low melting temperature (865°C)³ and is unlikely to be retained in BLA at the >1100°C necessary to remove ~18% melt⁷. A Pt-rich alloy phase is more likely to be refractory enough to be retained during high-degree melting. Such an alloy is distinct from the analyzed Fe-metal and was not identified in the studied thin sections. This alloy is not present during terrestrial mantle melting, likely due to low Pt abundances leading to Pt-undersaturated melts. Identification of this Pt-alloy in olivine-rich achondrites will elucidate its likely formation mechanism.

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References: [1] Keil K. (2014) *Geochemistry*, 74(3), 311-329. [2] Day J. M. D. et al. (2012) *GCA*, 81, 94-128. [3] Day J. M. D. et al. (2019) *GCA*, 266, 544-567. [4] Crossley S. D. et al. (2020) *Meteoritics & Planet. Sci.*, 55(9), 2021-2043. [5] Day J. M. D. et al. (2015) *Meteoritics & Planet. Sci.*, 50(10), 1750-1766. [6] McDonough W. F. & Sun S.-S. (1995) *Chem. Geol.* 120, 223-253. [7] Horan M. et al. (2003) *Chem. Geol.* 196, 5-20 [8] Collinet M. & Grove T. L. (2020) *GCA*, 277, 358-376.